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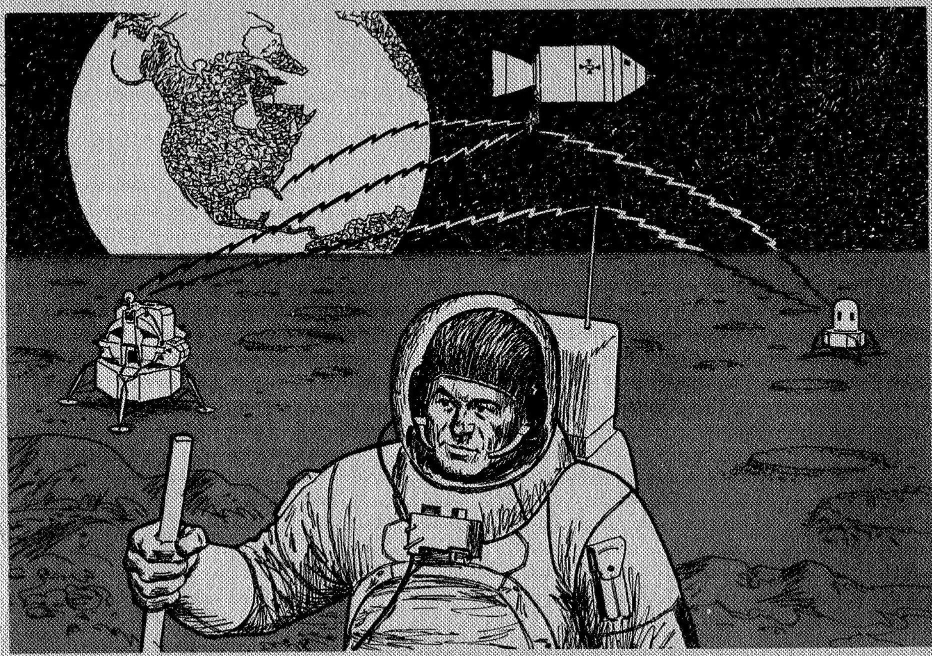

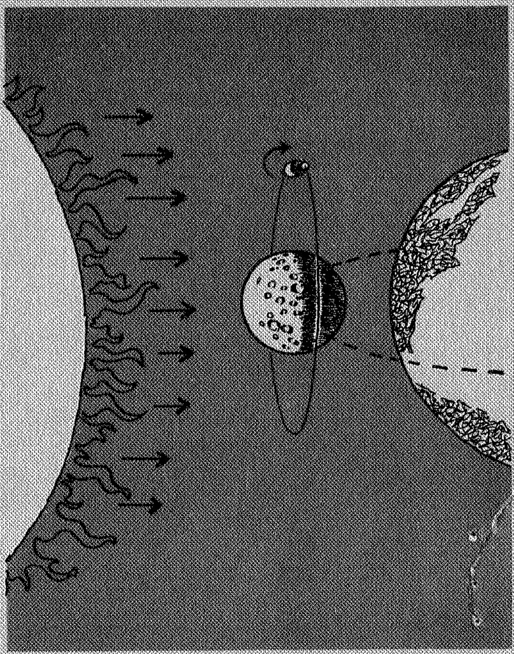

Extended
Lunar Orbital Rendezvous Mission

VOLUME III - SUMMARY OF RESULTS

SPACE DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION

SD 68-850-3

A STUDY OF AN EXTENDED LUNAR ORBITAL RENDEZVOUS (ELOR) MISSION

CONTRACT NAS2-4942

FINAL REPORT
VOLUME III SUMMARY OF RESULTS

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FOREWORD

This is Volume III of a report recording the results of a study of the Application of Data Derived Under a Study of Space Mission Duration Extension Problems to an Extended Lunar Orbital Rendezvous Mission (ELOR). The report consists of:

Volume I	Technical Analysis
Volume II	Supplemental Data
Volume III	Summary of Results

The results of the study are summarized in this volume to provide management with the highlights of the study and the major findings. The study was performed under Contract NAS2-4942 for the Mission Analysis Division of the Office of Advanced Research and Technology (OART), National Aeronautics and Space Administration, Ames Research Center, Moffett Field, Calif.

The work was performed under the direction of Roy B. Carpenter, Jr. Substantial contributions were made by the following subcontractor personnel, who provided data for this study and an earlier baseline study without cost:

1.	A.C. Electronics	Al Lobinstine
2.	Aerojet-General*	C. Teague
3.	AiResearch Division of Garrett Corp.	Joe Riley
4.	Allis Chalmers*	John Hallenbeck
5.	Allison Division of G.M.*	J.C. Schmid
6.	Bell Aerospace Systems*	T.P. Glynn
7.	Collins Radio	R. Albinger
8.	Dalmo-Victor Corp.*	R.L. Straley
9.	Eagle Picher Corp.	Jeff Willson
10.	General Time Corp.*	Fred Schultz
11.	Grumman Aircraft Engineering Corp.**	Hart Wagoner
12.	Hamilton Standard Division of UAC	R. Gredorie
13.	Honeywell Corp.	Jerry Mullarky
14.	ITT Industrial Products	R. L. Weir
15.	Marquardt Corp.*	J.B. Gibbs
16.	Motorola Corp.	Bill Crook
17.	Northrup-Ventura	T. Kanacke
18.	Pratt & Whitney Division of UAC	Jay Steadman
19.	Raytheon Manufacturing Co.*	H.A. Prindle
20.	RCA Corp (Camden & Burlington)	J. Heavey/S. Holt
21.	Radiation, Inc.	Wally Adams
22.	Simmonds Precision Products*	W.E. Nelson
23.	Westinghouse Corp.	C.W. Chandler

*Data supplied for baseline study.
**Performed under NASA Contract NAS9-6608

The study was based on data derived from the baseline study, a company-funded effort documented under NASA Contract NAS2-4214, and the mission systems design derived by the Lockheed Missiles and Space Company (LMSC) under Contract NAS8-21006.

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INTRODUCTION

The extended space mission has been the subject of many studies, some with the moon as an objective but most involving planetary exploration. All had one thing in common: they were to be attempted well in the future. With the Apollo project nearing fruition, however, the time has come to make plans for the next major effort. Unlike Apollo, many of the system functions required for an extended mission are developed to the point where they will satisfy existing requirements. In an environment where economy is essential, logical use of available hardware is an important step in the next space mission milestone.

The key question is then "What can we do with what we have?" This study is aimed at identifying the capabilities of existing space hardware as applied to a specific extended-duration mission. Extended-duration missions are constrained by two basic factors:

1. The ability to provide required consumables in a habitable environment

2. The increasing probability of a critical malfunction

The later factor has turned out to be the dominant one for the near-term missions, particularly where efficient utilization of available technology is desired. Therefore, means of minimizing the malfunction hazard for a specific mission were given special consideration in this study.

Some of the activities which led to this study are:

Past Studies

- Availability concept development—NAS9-3499 (1964-65)
- Apollo Extention System Studies (NAS9-5017 NR/SD and NAS9-4983 Grumman) (1965-66)
- Availability applied to mission systems—SD Funded (1966-1967)
- Availability applied to extended-life subsystems—Subcontractor Funded (1966-1967)
- Documentation of SD and subcontractor studies—NAS2-4214 (1966-1967)

Baseline Mission Study

- Lockheed definition of the ELOR mission—NAS8-21006

In pursuance of a planetary mission study under NAS9-3499, the "availability concept" was developed by SD for application to extended manned missions. It provided a mechanism through which the potential malfunction could be identified during the planning stages and dealt with in the system design so that the hazard level could be reduced to any desired level.

The "availability concept" is a technique that facilitates the determination of an optimum system and mission design. This is achieved through establishment of a safe and reasonable balance among system and mission performance, reliability, maintenance, operability, and controlled utilization. The result is a mission system with an exceptionally high probability that its functions will be available when and where required. The logic of this analytical technique is presented in Figure 1-2 of Volume I.

The extended lunar orbital rendezvous (ELOR) mission seems to present an economical candidate when compared with the more ambitious lunar or planetary missions. The Lockheed Missiles and Space Company (LMSC) studied an improved lunar cargo and personnel delivery system (NAS8-21006) which resulted in the definition of the ELOR mission. It provides for a three-man crew on the lunar surface for up to 90 days. The crew is to be housed in a direct lander shelter and the CSM and LM are to be dormant with a minimum of functions operating. The hardware requirements are based on maximum use of existing systems and minimum development cost.

As in the LMSC effort, SD studies indicate that the ELOR mission as a personnel carrier, together with one of several logistic missions, provide an attractive combination for extended lunar explorations using a minimum of new hardware. The subject of this study is the ELOR personnel carrier.

The study objective was to establish the feasibility of the ELOR concept as a personnel delivery system for post-1975 lunar exploration. It was to define the system hardware used from the Apollo program, identify requirements for new development, define the recommended operational concept, and identify the associated support requirements. The use of limited maintenance and repair was considered an essential part of the concept, within the constraints of the basic design. Modifications were to be held to a minimum. Specific objectives included:

1. To test the feasibility of using the Availability Concept for an extended manned mission and system design.

2. To determine the ELOR mission capability using contemporary hardware (Apollo command, service, and lunar modules)

3. To develop a quantitative assessment of key factors as they affect achievement of a probability of safe return of 0.99.

4. To determine the effect of the recommended design on the development program.

The key factors to be assessed included (1) space mission extension capability as a function of the operational concept and through the application of maintenance and repair; (2) quantity of maintenance and repair actions and the resultant crew work load;

(3) type of maintenance and repair actions and extravehicular activities; (4) weight penalty imposed as the result of having to perform maintenance actions or add redundancy; (5) optimum operational concept as it affects safe crew return; and (6) the effect of potential design improvements.

The study was conducted as indicated by the study logic of Figure 1. A systems engineering approach was selected, even though subsystem requirements were defined by the LMSC effort. A detailed independent analysis was accomplished through the functional flow process. As a result, functional requirements were derived by mission phase from which duty cycles, downtime, and operational constraints were defined. The Apollo Design Reference Mission (DRM 2A) provided much of the required data.

These data, together with the data from the former SD study (NAS2-4214), permitted a complete definition of mission requirements and constraints. Only the lunar area operations were stressed, however, because the remainder were the same as the Apollo mission. Subcontractors were given these data and asked to define subsystem design details and conduct the availability analysis as defined by the logic in Figure 1-2 of Volume I. The subsystem analysis data were compiled and reassessed in terms of the effect on the overall mission. A final concept was recommended and the support requirements defined.

The study was based on the mission (ELOR Personnel Delivery, 3 Men up to 90 days, Operational 1975) defined in the preliminary LMSC report of June 1968.

Data generated under the earlier SD study were used to establish crewmen capability, systems logic, maintenance technology, and potential alternate solutions. In addition, much of the system data were directly applicable to the support requirements definition. Assumptions used in the study were:

1. The mission actually provided 90 days in the lunar area (a worst-case situation)
2. The Apollo profile (DRM-2A) was applicable to all mission phases except those in the lunar area.
3. A lunar shelter was already successfully landed reasonably near the LM site (within 1000 feet).
4. Abort may be required at any time but is constrained by the rendezvous window which varies with landing site and plane change capability.
5. Design goals must equal or exceed Apollo criteria.
6. Maintenance and repair were permitted where an identified requirement existed.
7. Existing hardware must be used to satisfy new functions required where possible.
8. The CSM was parked in a lunar orbit with the CSM roll axis perpendicular to the sun's rays and rotating at 0.5 rpm.
9. The LM and shelter could be anywhere on the lunar surface.

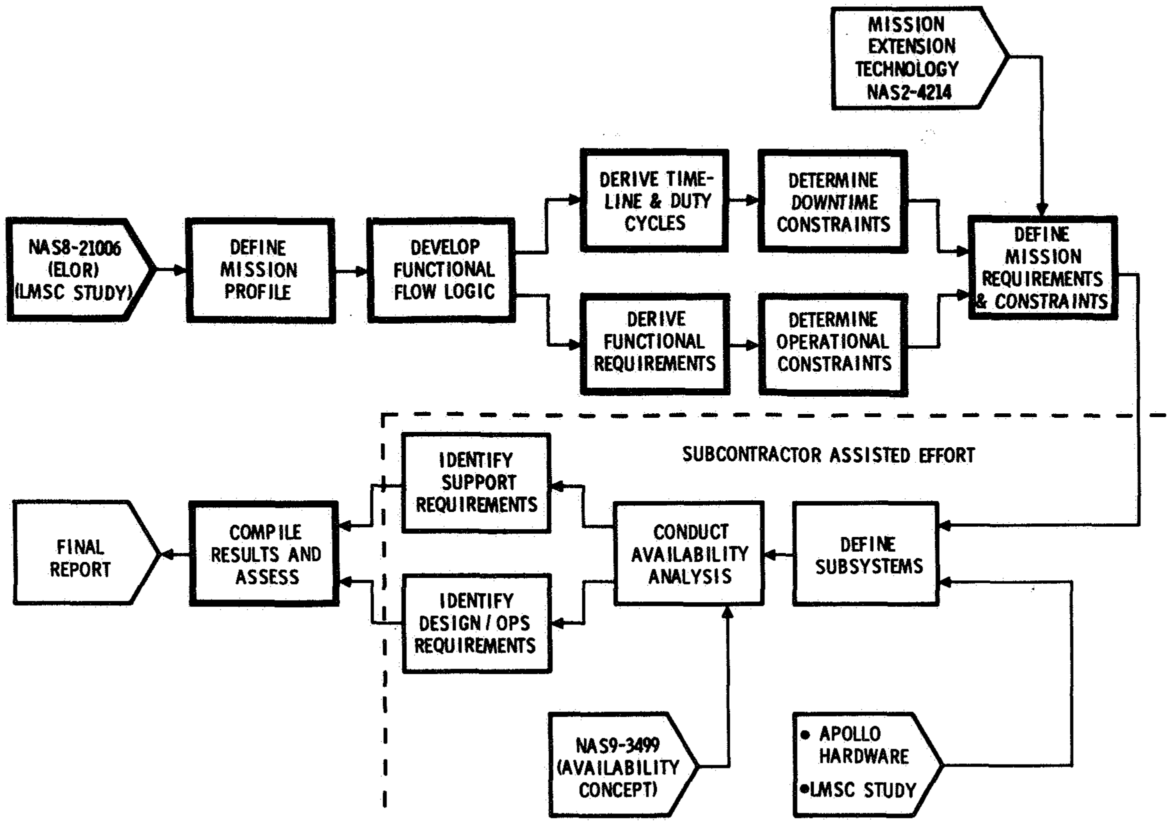


Figure 1. ELOR Study Logic

10. The recommended LMSC baseline was flexible and could be modified to maximize mission safety and success.

11. The Apollo hardware was considered qualified for the design reference mission.

ELOR MISSION

BASELINE MISSION

The ELOR mission is characterized in Figure 2. The activities of specific interest to this study involve operations in the lunar area, where they differ greatly from the Apollo DRM. Figure 3 is a functional flow diagram of the first two levels for the CSM and LM in the lunar area; also included is the association with the lunar shelter interface.

Two Saturn V launches are required, one for the lunar shelter/logistic vehicle and one for the ELOR spacecraft. The lunar shelter/logistic vehicle is sent to the lunar surface well in advance of the ELOR spacecraft. After arriving in lunar orbit, the ELOR vehicles will acquire a lunar orbit so that the desired point on the surface may be reached. The LM then is manned and separated from the CSM, which is switched to the quiescent mode by remote control. The CSM quiescent mode involves orienting the roll axis 90 degrees with respect to the sun's rays and initiating a slow roll (barbecuing). When the wobble exceeds ±20 degrees, it is immediately cancelled out. Only the systems required to maintain and monitor the quiescent state are left functioning.

The LM vehicle descends to the appropriate spot on the lunar surface and within 1000 feet of the lunar shelter. The LM is evacuated and placed in a quiescent state, not to be reoccupied until departure or abort. Only the functions required to maintain and monitor the quiescent state are left functioning.

FUNCTIONAL REQUIREMENTS SUMMARY

The mission system functional requirements were derived through detailed analysis of the functional flow logic of the mission (see Section 2 of Volume I). The vehicle requirements are identical to the Apollo DRM for all manned phases except for the third man in the LM. Therefore the functional capabilities of the modules must meet the manned phase requirements for the ELOR mission without change, except for provisions for the third man in the LM.

Since the manned phase requirements may be considered fulfilled, this study was concerned with the unmanned or quiescent phases, plus the three-man LM. Another exception involved manned intervention for maintenance or repairs, in emergiencies or just before departure, where feasible. The basic criteria applicable to these phases were (1) the quiescent state must be established and maintained, (2) this state must not degrade the dormant functions, and (3) it must be feasible to return to normal operations upon command.

The results of the functional requirements analysis are presented in Tables 1 through 3. The requirements delineate functions required of the CSM, LM, and shelter interface imposed by the quiescent mode of operation and the third man, as well as the need for safety assurance and the need for reuse for earth return.

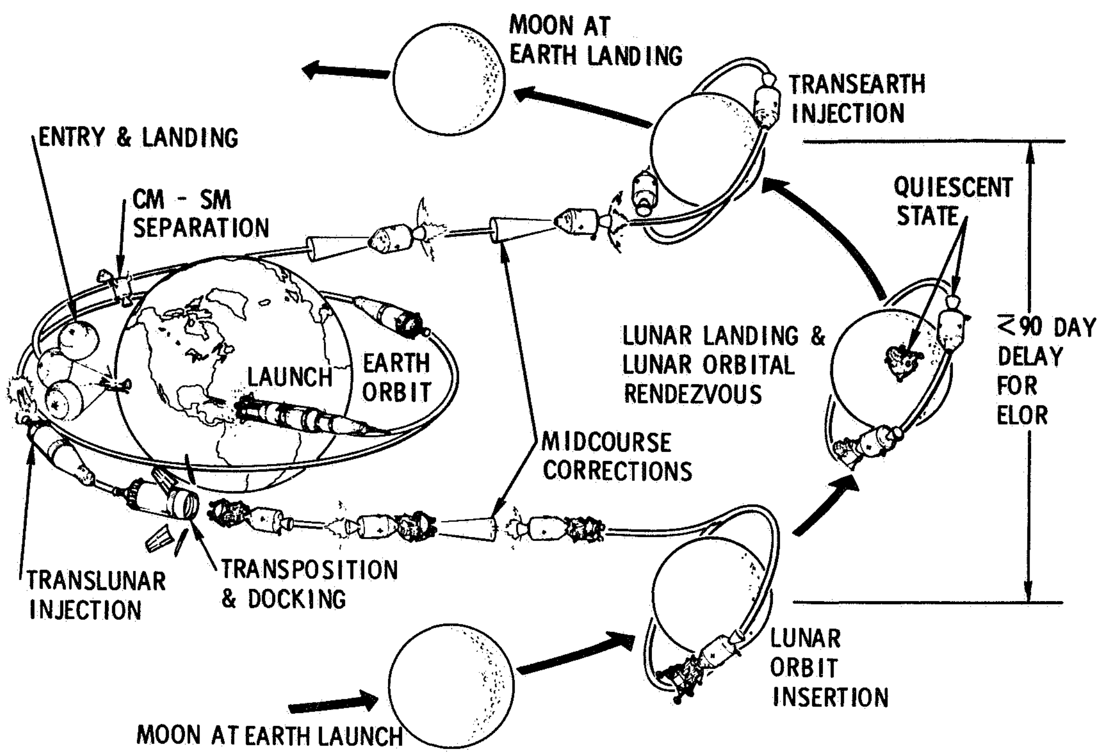


Figure 2. Apollo ELOR Design Reference Mission Plan

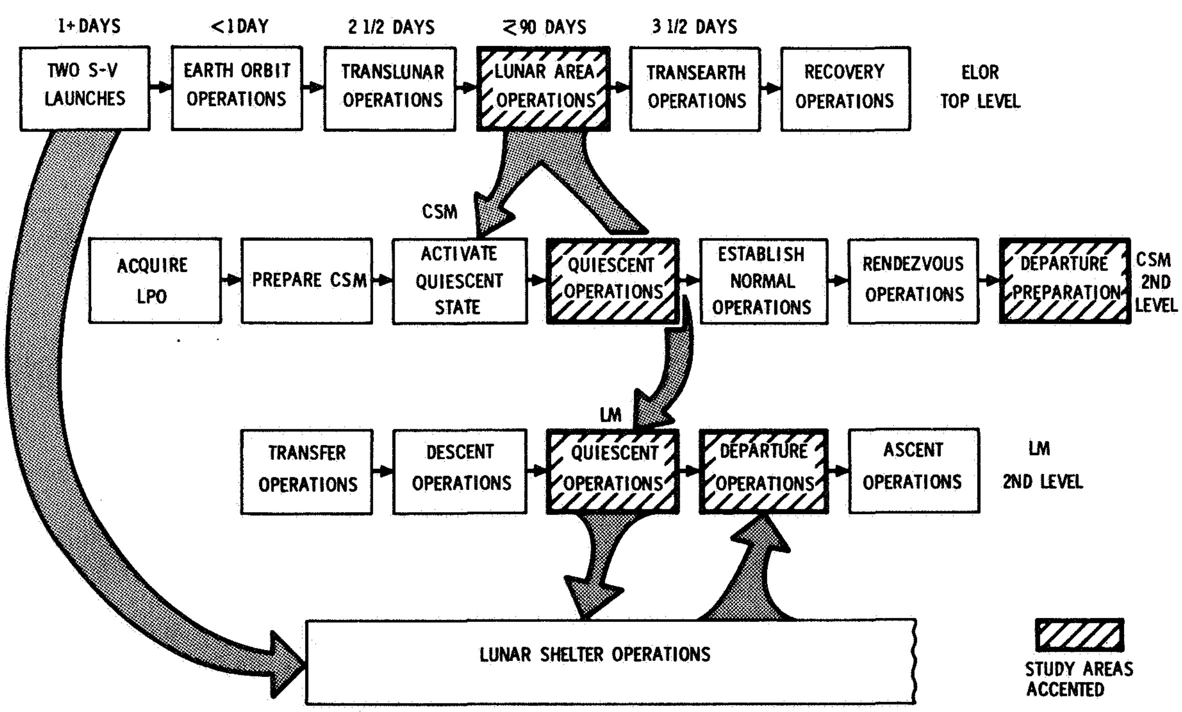


Figure 3. ELOR Mission Flow

Table 1. CSM System Functional Requirements, 90-Day Storage in Lunar Orbit

System/Function	Requirements and Constraints
Stability Control	Limit spacecraft instability to the safe limits Provide required stability for docking operation Permit use of orbit-to-surface & earth communication links Control orientation with respect to sun for temperature control
Internal Temperature Control	Limit temperature excursions on cabin wall to between +40 to +100 degrees Assure water temperature is above freezing Assure protection of temperature-sensitive equipment
External Temperature Control (Heat Shield and RCS)	Assure even barbecuing of heat shield and other structure Assure RCS engines and feed system do not freeze
Pressurization of Cabin	Maintain minimum required atmospheric pressure at about 0.5 psia
Status Assessment	Assess cabin pressure Assess temperature in critical areas and systems Assess spacecraft kinematics Assess heat shield temperature in critical areas Assess power plant status Assess fuel reserves Provide for critical funtion failure alarm
Remote Control Capability	Provide for switch between redundant systems and functions Provide attitude & stability control for docking Provide emergency control of orbital position & plane Initiate checkout or diagnostic routines on command
Lunar Orbit to Surface Link	Relay alarms to crew in time to facilitate abort Relay status of systems critical to safety to earth and to surface crew
Electrical Power Supply	Provide electrical power for quiescent state control Be capable of remote start-up of any secondary source to full power for rendezvous or in case of impending failure of operating unit Indicate when failure is imminent or probable Minimum of 2500 hours life
Maintenance and Repair Support	Diagnostic routines to isolate failures in critical system functions Spares complement to support repair or replacement Tools to support maintenance on moon EVA support system Ability to use LM system components
Special Facilities (EVA Support)	Easy access to CM interior by one EVA crew member Ready access to O_2 supply, via an umbilical at point of ingress Handholds on spacecraft exterior
Up-Data Reception	Update or regenerate guidance computer memory Provide link for remote control (command link) from earth, from LM, and from lunar shelter Provide timing data from earth
Increased Environment Protection	Meteoroid hazard Radiation hazard

Table 2. LM System Functional Requirements, 90-Day Storage on Lunar Surface

System/Function	Requirements and Constraints
Remote Control of CSM	Provide ability to control CSM position from LM during active rendezvous Provide control of quiescent state control systems Provide ability to control CSM stability remotely
Crew Transfer Aids	Provide EVA umbilical for preparatory activity Provide tether, reel, and disconnect at LM Provide personnel life support system to handle the EVA phase, about 1 hour at a higher work level Provide EVA maneuvering unit or method of capturing uncontrolled CSM
CSM Status Monitor	Provide minimum monitoring of CSM status for safety of crew for rendezvous operations, ascent, and descent Provide alarm as required
Command Link	Provide link to relay remote control commands to CSM during LM descent or ascent
Provisions for Third Man	Seating arrangement Structural support Fuel and consumables ECLS functions
Electrical Power	Continuous electrical power for quiescent state operations
Internal Temperature Control	Limit excursions to between +40 to +100 F Provide protection to temperature-sensitive equipment
Internal Pressure Control	Maintain cabin pressure at about 0.5 psia
External Temperature Control	Limit aft equipment rack temperature to between +40 and +100 Provide for thawing RCS engines Prevent fuel and water tank freeze
Maintenance and Repair Support	Provide spares Establish diagnostic routines Provide tools for maintenance support Provide for CSM/LM component interchangeability Provide ready access to potential failures
CSM Tracking/Locator	Provide independent knowledge of CSM position
Data Link	Provide memory restoration data from earth Provide timing data from earth

Table 3. Lunar Shelter Functions, CSM and LM for ELOR

System/Function	Requirements and Constraints
CSM Status Readout	Indicate status of critical orbiting CSM systems on at least a go/no-go basis Provide an abort alarm system
Alarm System	Provide a method of notifying lunar party personnel of an impending emergency or abort
Remote Control of CSM	Provide remote control of redundant functions critical to CSM integrity and crew safe return Provide ability to start up systems required for rendezvous (LM system may suffice) Provide start-up control of the electrical power source
Command Link	Provide link to facilitate remote control
LM Status	Provide for remote monitoring of LM status and/or visual inspections

SUBSYSTEM OPERATING TIME AND RELIABILITY RAMIFICATIONS

An analysis of subsystem functional timelines and the resulting duty cycles yields an estimate of the potential reliability problem. This analysis can do much to close the credibility gap associated with the estimation of the probability of safe return (P_s).

It is well known that reliability (R) is expressed as $R = e^{-\lambda t}$, where λ = failure rate and t = operating time. From this expression it is obvious that R decreases with time (t), and therefore the probability of safe return P_s is very sensitive to system operating time. It is therefore obvious that the systems that operate longer or more often for the ELOR mission than for the DRM will have a higher probability of a failure. It is equally obvious that the reverse should be true.

Given this basic premise, a comparison of the Apollo and ELOR system function duty cycles (Tables 4 and 5) reveals some important facts about system reliability problems. In general it was found that the ELOR mission required the CSM systems associated with the manned phases to operate about 50 hours less than for the Apollo DRM. The LM is required to operate about 14 hours less. This represents a drop of about a 25 percent in operating time for both vehicle systems and a proportional increase in R and P_s. In most cases, even the on-off transients are expected to be less for ELOR.

The quiescent-state operation requires about 2200 hours of operation for the system functions providing quiescent state control. In every case except RCS and propulsion engines, however, the functions involved were new and independent or involve only a small portion of the manned system functions.

The resulting picture indicates that the manned phases can be safer than the Apollo DRM and that the safety of the ELOR mission depends primarily on establishing and maintaining the required quiescent state, equivalent to Apollo storage conditions.

SYSTEM FUNCTION DOWNTIME CONSTRAINTS

The requirements analysis included consideration of system function outages, (Section 2.7 of Volume I). The results may be summarized by stating that any of the CSM and LM functions except one could be malfunctioning for more than 24 hours during the unmanned phases without introducing any hazard which would lead to the loss of the crew. The one exception involves the orbiting CSM attitude and roll control function (ESS) and since it could be commanded to return to the manned stabilized mode in the event of ESS failure, this provides the required backup function. Subsequent failure in this mode would only result in CSM drift which can be dealt with through EVA during the rendezvous operations.

Manned phase outages were limited by remote events such as rapid decompression from a meteoroid where for the CSM, from 10 to 30 minutes is available to take a compensating action. The next most critical event involved the CO_2 removal function, and between 3 and 6 hours is available for the repair action.

QUIESCENT STATE

It has been shown that a ELOR mission can be safer than the Apollo DRM, provided a quiescent state that is not detrimental to the inactive system functions can be established and maintained. The resulting state could be made analogous to storage life conditions where for Apollo the components must survive three years without any detrimental effects.

Table 4. CSM Systems Duty Cycle Evaluation

Subsystems	Apollo DRM (hours)	ELOR In Transit (hours)	ELOR Quiescent (hours)
Electrical Power (hours)	200	152	2200**
Environment Control (hours)	200	152	2200*
Stability Control (hours)	200	152	2200**
Communications (hours)	50	30	90*
Reaction Control (cycles)	1000	4490 Total	
Propulsion (seconds)	550	600 sec. (max)	0
Guidance & Navigation	No Appreciable Change		0

*Uses part of in-transit system
**New and substantially independent function

Table 5. LM Duty Cycle Evaluation

Subsystems	Apollo DRM (hours)	ELOR In Transit (hours)	ELOR Quiescent (hours)
Electrical Power (hours)	44	30	2188**
Environment Control (hours)	44	30	2188*
Stability Control (hours)	44	30	0
Communications (hours)	44	30	24*
Ascent Propulsion (seconds)	460	510	0
Descent Propulsion (seconds)	420	520	0
Reaction Control	No Appreciable Change		0
Guidance & Navigation	No Appreciable Change		0

*Uses a small percentage of the in-transit systems
**New and independent function

A study performed for RADC/USAF (TR-67-307) indicates that the shelf or storage life of a system depends on the applied stresses. The stresses that most affect the systems are temperature, acceleration, and pressure. Wide ranges in the first two of these stresses are encountered in earth storage and transportation; therefore, somewhat more conservative values for the quiescent mode should assure no degradation. A temperature range from +40 to 100 F, acceleration of less than 1g, and 10 percent humidity were therefore recommended and designed for.

Less is known about the effects of lower pressure, but supplier data derived during Apollo tests at the component and subsystem level indicate that there are no deleterious effects on Apollo-qualified components at pressures above 10^{-4} torr. However, for the purpose of this study 0.5 psia was used and recommended for the CM and LM interiors.

THE MISSION SYSTEM (THE BASELINE SPACECRAFT)

By contract definition, the baseline ELOR spacecraft consisted of a modified Apollo CSM and a three-man version of the LM, as defined in NAS8-21006. The lack of detail in that study necessitated an expansion and reevaluation of some of the recommendations based on new and more explicit Apollo/LM data. A more detailed description of the baseline spacecraft, its systems, subsystems, and functions resulted. Specific hardware was identified to the detail necessary to perform the subsequent availability improvement analysis.

The possibility of an alternate CSM design emerged with a much more conservative modification and supporting development program requirement. The major differences center around the electrical power requirement and its source for the dormant mode.

ELOR-CSM (RECOMMENDED CONCEPT)

The recommended CSM concept for the ELOR mission requires no extensive modifications; they are limited to the addition of a few functions as indicated in Tables 6 and 7. Some components in the CM must be shuffled to permit the installation of two modified SNAP-27's. The modifications for the concepts considered do not affect the external appearance (Figure 4) or structural members in any way.

The drastic variations between the NAS8-21006 and SD concepts (Table 7) came about solely because of the differences in electrical power source. The recommended concept involves replacement of the three existing Pratt & Whitney fuel cells with two of a later, lighter version and installation of two modified SNAP-27 radioisotope thermoelectric generators (RTG) in the outer perimeter of the CM (Figure 4). The concepts are evaluated in a later section.

Changes to the CM as recommended in Table 6 are described in detail in Section 4. 1 of Volume I. The result is a personnel module with the desired 90-day extended mission capability for a weight increase of only 335 pounds in the CM, after all of the modifications and new functions are added.

Changes to the SM as recommended in Table 7 are described in detail in Section 4. 2 of Volume I. The result is a service module requiring but few modifications and a maximum wet weight decrease of 637 pounds; the dry weight is actually 14 pounds lighter than Block II Apollo and 6110 pounds lighter than all fuel cell concepts. The actual total SM weight can vary considerably as a result of flight-profile and transit-time considerations; however, it does not need to exceed the present 40, 000 pound fuel capacity.

ELOR-CSM (ALTERNATIVE CONCEPT)

This concept was proposed in the NAS8-21006. It involves minor modifications to the CM and extensive modification to the SM. The overall CSM weight difference is more than 5800 pounds over the Block II configuration.

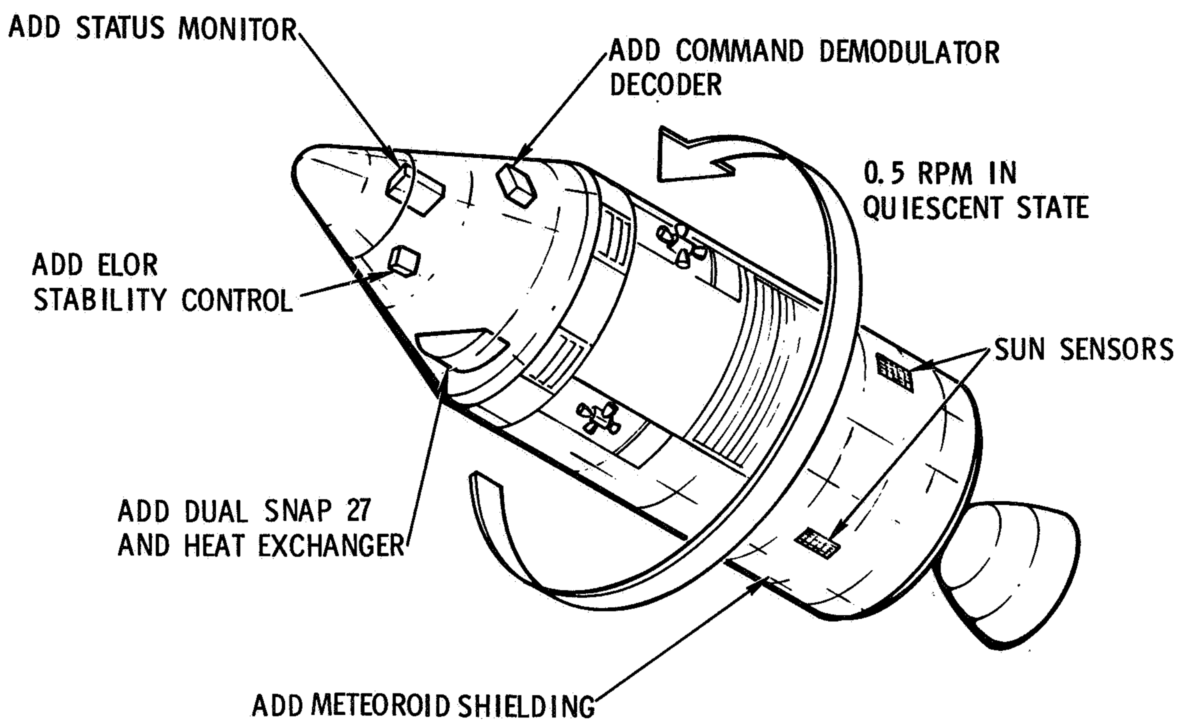


Figure 4. CSM Modifications for ELOR

The CM for this concept is substantially the same as Block II Apollo except for the additions listed in Table 6. It weighs 100 pounds less than the recommended concept and does not require the rearranging of components in the outer compartment. The weight increases by about 235 pounds over the Block II configuration.

The SM changes are extensive as indicated in Table 7. Only the moldline and the engines remain unchanged. The requirements for additional fuel to power the one fuel cell for the 90-day quiescent phase adds about 1000 pounds to the dry weight and 5573 pounds to the wet weight. Further, because of the desire to not change the size and shape, a relatively new technology is required—subcritical cryogenic fuel storage. The concept has not yet been fully developed and would represent a pacing item. For that reason and because of the extensive modifications required, this concept is not recommended. However, it is considered feasible for 1975.

Some meteoroid protection will be required for both concepts; the resulting weight penalty will be between 270 and 400 pounds of shielding.

ELOR-LM

Both LM vehicle stages require more extensive modifications than the recommended CSM because of the addition of a third man and his supporting functions. In spite of this, the modifications have little affect on the moldline and will not affect the SLA (Figure 5).

Modifications for the ascent stage are listed in Table 8 and explained in detail in Section 4.3 of Volume I. The third man and quiescent state control dominate these requirements. The descent stage is modified as indicated in Table 9 and explained in Section 4.4 of Volume I. These changes are dominated by the requirement for the additional fuel and the requirement for continuous electrical power for 90 days. Again a modified SNAP-27 is recommended as the source of both electrical power and heat energy.

Table 6. CM Subsystem Changes

Subsystems	Recommendation	Weight Changes (pounds)
Electrical power	Change batteries	+33
	Add SNAP 27A (two)*	+100*
Environmental control	Modify water-glycol loop	+20
	Add quiescent state control	+3
Stability control	Add ELOR control function	+10
Communications	Add status monitor	+18
	Add command demodulator/ decoder	+4
	Modify USBE (simple) and	+6
	add omni antenna	+14
	Modify up-data link	0
Instrumentation	Add sensors/signal conditioner	+2
Other	Add spares/redundancy	+111
	Add meteoroid protection	+14
		+335*
*100 pounds less with fuel cell concept		

Table 7. SM Subsystem Changes

Subsystem	Recommendation	Fuel Cell (pounds)	SNAP 27A (pounds)
Electrical power	Replace fuel cells	-258	-324
	Modify plumbing	+10	+30
Reaction control	Modify tank bladders	0	0
	Increase fuel capacity	+96	0
Propulsion	Increase fuel capacity	+50	0
	Add helium storage	+10	0
Cryogenic storage	Replace and relocate cryogenic storage tanks	+678	0
Instrumentation	Add sun sensors	+4	+4
	Modify sensor package	+3	+3
Structure	Add meteoroid shielding	+400	+273
		+993	-14
	Increased consumables	+4580	-623 (min)*
Total change (based on SC 107 with full SPS tanks)		+5573	-637
*Depends on lunar launch window and transearth injection window size; a full load of fuel (40,000 pounds) would permit maximum departure windows.			

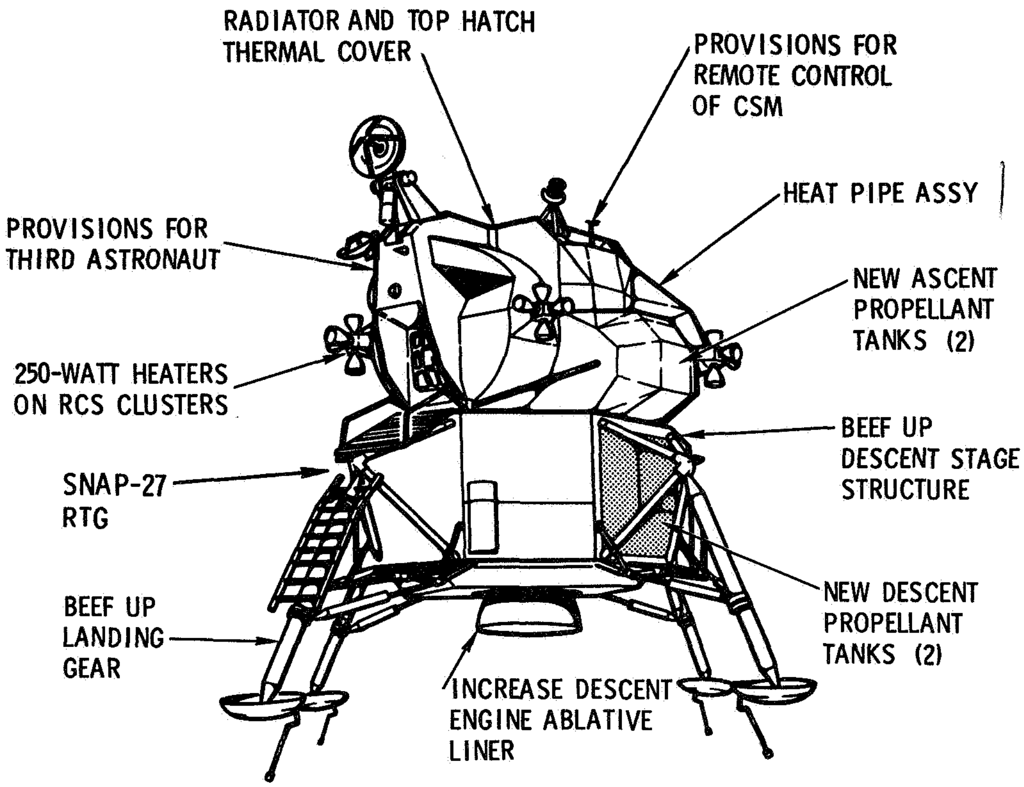


Figure 5. LM Modifications for ELOR

The large increase in LM vehicle weight, almost 500 pounds in the ascent stage and over 1500 pounds (dry) for the descent stage, imposes a proportionally large increase in the required fuel loads and the associated tankage. The resulting fuel requirement was increased by nearly 4200 pounds and the injected weight by 6900 pounds.

ELOR-CSM ELECTRICAL POWER ALTERNATIVES

It has been shown that the selection of an electrical power source is paramount to the design of the CSM and, in particular, the SM. For that reason it is necessary to select the appropriate concept as early as possible. To this end, a comparative analysis is presented in Table 10.

Note that the data seem to indicate that all of the criteria except one—power capacity—favor the RTG concept. The RTG output level is only 200 watts maximum versus 2500 watts; however, higher power is an advantage only if the power is required. The large weight difference and the marginal parasitic heat available make use of fuel cells undesirable where they can be avoided. The potentially marginal power output of the RTG can be augmented by batteries during peak loads. The RTG can recharge as required. Further, the excess parasitic heat will keep both CM and SM internal temperature well above the danger level and will not permit any radiators to freeze, which may not be true of the all-fuel-cell concept.

The large reduction in required power came about because of optimum usage of RTG parasitic heat where heating was required, rather than electrical heaters. The glycol loop provided the transfer medium.

More study is required in this area to verify the estimates used for the analysis.

Table 8. LM Ascent Stage Changes

Subsystems	Recommendations	Weight Changes (pounds)
Electrical power	Replace batteries	+26
Environmental control	Add heat pipe assembly	+3
	Add radiator and modify heat loop	+42
	Modify atmospheric control loop	+54
Guidance and control	Add program coupler assembly	+25
	Add remote controller for CSM	+15
Reaction control	Add quad heaters	+4
Communications	Add command receiver-decoder	+25
Propulsion	Modify propellant tankage	+43
Structures and crew provisions	Add provisions for third man	+139
	Provide meteoroid and thermal shielding	+85
Instrumentation	Add status monitor and modify sensors	+14
	Empty total	+475
	Third crewman	290
	Increase in stage consumables	601
		+1366

Table 9. LM Descent Stage Change

Subsystem	Recommendations	Weight Changes (pounds)
Electrical power	Replace batteries	+691
	Add SNAP 27 (modified)	+52
	Add voltage regulator and battery charger	+60
	Add third PLSS batteries	+20
Descent propulsion	Replace propellant tankage	+177
	Add ablative to engine	+7
Structure	Beef up stage structure	+400
	Beef up landing gear	+100
	Dry stage weight change	+1507
	Increase in stage consumables	+3544
		5051

Table 10. CSM Electrical Power Alternatives

Concepts	3 FC, 1-90 Day Ops	2 FC + 2 SNAP 27's (RTG)
Weight changes	+5163 lb (SM)	+100 lb (CM)
Affect on P_s	≈0.994	0.99999
CSM power required *(watts)	237 average 307 peak	124 average 191 peak
Power capability (watts)	2500	140 to 200 (max.)
Modifications required	Extensive SM for fuel storage	Minor CM relocation
Development status	Qualify FC Develop fuel storage system	Designate Quality heat pipe
Parasitic heat output	3750 Btu/hr	9880 Btu/hr

*Heating requirements excluded. CM requires +300 Btu/hr with present coating (e + 70°F). SM can vary considerably. FC = fuel cell

ELOR MISSION IMPLICATIONS

ANALYTICAL TECHNIQUE

Estimating Reliability - The Baysian Approach

Estimating reliability in the classical sense has depended on the conventional statistician who requires much test data on the specific system. This is an expensive and impractical means of assessing modern space system reliability status.

Recently there has emerged a new and more practical approach to reliability estimation based on the logical application of all available applicable data; it makes use of Baysian statistics. Briefly, it accepts all available test data, including those accumulated on prior systems, and takes into account the effects of modifications. As a result, failure modes that have been eliminated by design actions are no longer included in the system reliability estimate. The end result is a more realistic estimate of mission systems reliability and subsequent safety. (See the Minutes of Session 7A of the 1968 Annual Symposium on Reliability.)

This approach is used by SD in estimating space system reliability and safety because of its conformance to practical engineering principles and economic constraints. The implications on the ELOR Mission are self evident; the data derived from the Apollo program serves as an a priori index as to the potential success of the ELOR, provided the aforementioned conditions are met.

Evaluating ELOR Mission Effectiveness

Effectiveness has been used as a measure of accomplishment; but it must be related to some tangible objectives or another system. A mission achieves maximum effectiveness when it permits accomplishment of the objective and all subobjectives within the allotted time. The ELOR spacecraft (CSM/LM personnel delivery system) must therefore permit the full 90-day stay on the lunar surface and return the three-man party safely to the appointed spot on the earth's surface to be completely effective or achieve maximum effectiveness. Applying this definition to the ELOR mission, the measure of effectiveness has two factors:

1. Stay time, expressed as: the probability of completing the 90 days without a CSM or LM failure requiring abort (P_{90}).

2. Crew safety, expressed as the probability of crew safe return (P_s).

From these the probability of having to abort or leaving before the end of the 90 days (P_a) is:

$$P_a = 1 - P_{90}$$

P_s is not basically dependent on stay time because abort can be initiated at any time deemed necessary to assure crew safe return, constrained only by the rendezvous and departure windows. It is only dependent on time in the sense that the longer the stay time, the greater the possibility of a crew-sensitive failure. However, this dependency on time can be virtually eliminated through application of the Availability Concept. This is accomplished through a pre-planned compensation for each potential failure mode.

ELOR effectiveness is therefore a function of both P_s and P_{90}. However; since they are not mutually exclusive, they must be evaluated separately.

Sample Analysis

The analytical technique used throughout the study depends on the use of reliability data in the relative sense only (Figure 6). The expected operating cycle data could have been used as a reliability estimator except that the difference in function complexity and other hazard inducing factors must be accounted for. Relative unreliability facilitates the identification of system failure potential (weak links) and the planning for mission safety improvements.

As indicated in Figure 6, all functions that could contribute to the probability of safe return (P_s) are identified in logic form. Each is evaluated against three influencing factors that make up the failure hazard: (1) the so-called random incident, (2) crew-inducted anomalies, and (3) environmentally induced hazards. Each factor is assessed in relation to the individual functions to determine if and how a failure could occur; these are put into a fault tree form. Each tree is subsequently assessed for total contribution to unreliability. They are listed in order of unreliability with the weakest link on top and expressed to one significant digit. The hazards are then evaluated as to failure mode and potential solutions as indicated in the logic for the Availability Concept (Figure 1-2 of Volume I) where maintenance and repair are given prime consideration.

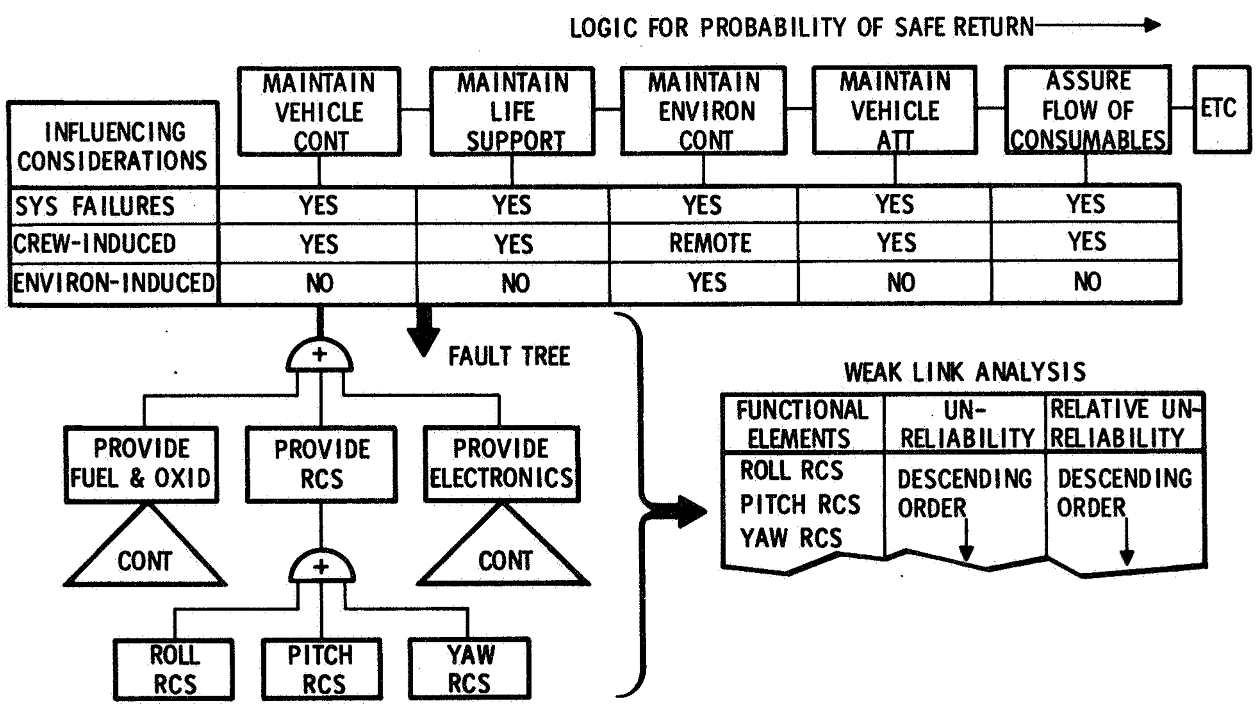


Figure 6. Identifying Crew-Sensitive Functions and Elements

Two examples were selected to demonstrate the analytical technique and establish the validity of the study results: CSM stability control for the quiescent phase (Figure 7) and LM-heat transport loop, quiescent phase (Figure 8).

Figure 7 presents initial P_{90} (R_o) of the CSM's stability control function during the quiescent phase. The stability control must control the CSM roll around its axis and cancel any wobble that exceeds 20 degrees. The logic diagram indicates that there are three weak links—components whose R_o is an order of magnitude less than the others. Some form of fix is in order to improve the function's contribution to P_{90} and reduce the potential contribution to the probability of abort (P_a) since loss of this function requires abort.

The fixes indicated in the associated table accomplished the purpose. Since the CSM is inaccessible to the crew during the quiescent phase, planned maintenance is impractical until crew return. A form of redundancy and operations control was sufficient to reduce P_a to a reasonable value. The resulting P_{90} would also be much better, probably exceeding 0.999. The effect on P_s depends on crew ability to abort from the lunar surface and the command link reliability.

Figure 8 presents R_o/P_s data relevant to the LM heat transport loop as applied to the quiescent phase. Again note that three components exhibited an R_o order of magnitude lower than the rest. In this case, the crew could have access to the vehicle for maintenance; therefore the pump motor could be replaced when the design permits. The temperature sensor function was improved by using more sensors than required but by dispersing them throughout the sensitive areas. The accumulator was impractical to replace, and a redundant one would serve the purpose. Failure of this function could affect P_s since a portion also is used during manned operations.

ELOR MISSION CAPABILITY

Command and Service Module Effectiveness

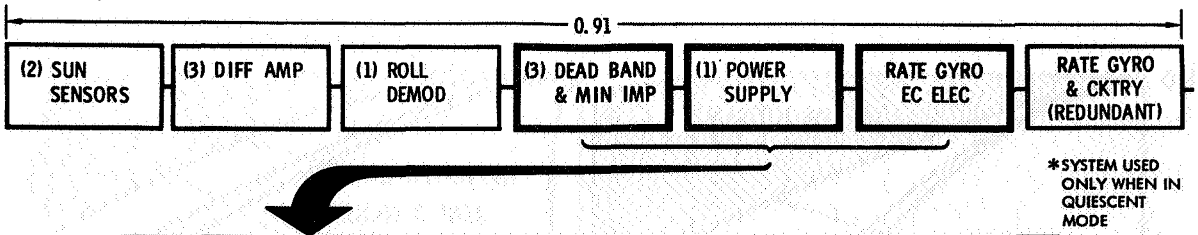
The CM and SM systems were evaluated as in the foregoing in Sections 4.1 and 4.2 of Volume I, and the results are presented in Tables 11 and 12. The cumulative effects of these recommendations and the resulting mission potential is expressed as a function of lunar orbit stay time in Figure 9.

The recommended modifications raise the Block II P_{90} to about 0.65; the addition of some switchable and automatic redundancy along with a minimum provision for maintenance would raise the CSM ELOR contribution to P_{90} to more than 0.99. The one remaining weakness in the CSM is the stability control function for the quiescent state. It was found that even this area could be improved over the 0.993, but better data are required to make a final judgment. In any event, a failure will only affect the requirements to abort and crew survival would be unaffected.

The resulting probability of having to abort (P_a) before the 90 days due to a CSM failure is expected to be less than one chance in 100.

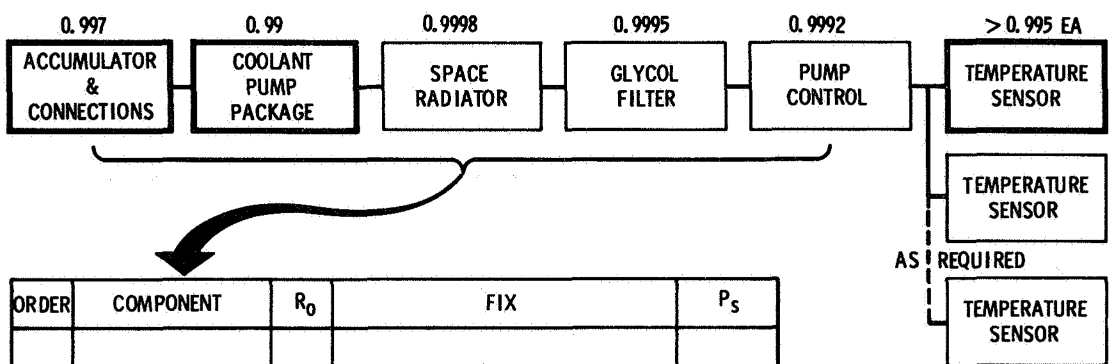
Lunar Module Effectiveness

The LM ascent and descent systems were evaluated in Sections 4.3 and 4.4 of Volume I, respectively, and are summarized in Tables 13 and 14. The cumulative results of these recommendations are presented in Figure 9, where the various



ORDER	COMPONENT	R_0	FIX	P_{90}
1	RATE GYRO / EC	0.94	STANDBY REDUNDANT COMPONENTS	0.998
2	DEAD BAND & M.I.	0.98	SWITCHABLE REDUNDANT (3 OF 4)	0.99991
3	POWER SUPPLY	0.99	REDUNDANT COMPONENT (OPERATING)	0.99999
4	SUN SENSORS	0.997	NONE REQUIRED	0.997
7	DIFF AMP	0.9998	NONE REQUIRED	0.9998
	SYSTEM*	0.91	————	0.993+

Figure 7. Sample Analysis: CSM Stability Control, ELOR Quiescent Phase (New System)



ORDER	COMPONENT	R_0	FIX	P_S
1	COOLANT PUMP	0.99	SPARE PUMP PACKAGE	0.9999
2	TEMP SENSORS	0.995	USE ADDITIONAL SENSORS, NOT NECESSARILY CO-LOCATED	0.99997 EA
3	ACCUMULATOR	0.9997	REDUNDANT ASSEMBLY	0.999992
6	PUMP CONT	0.9992	NONE REQUIRED	0.9992
	SYSTEM	0.98	————	0.998

Figure 8. Sample Analysis: LM Heat Transport Loop, Quiescent Phase

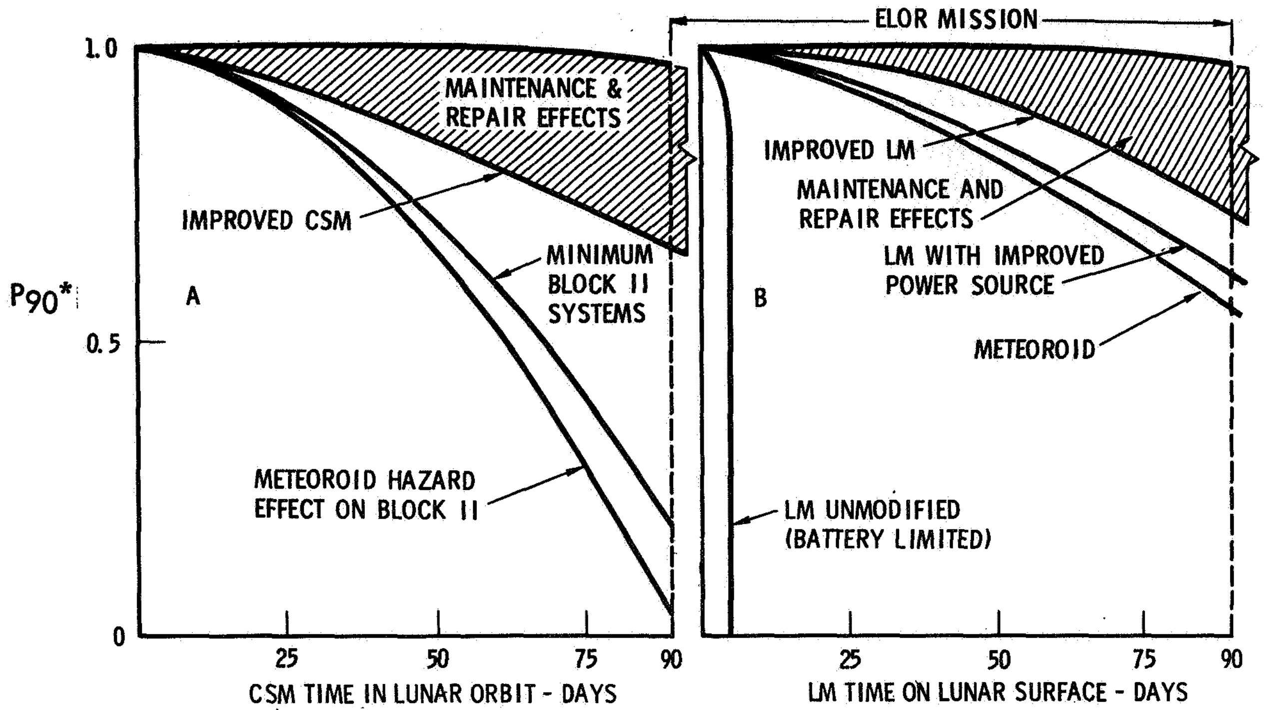


Figure 9. Effect of Design and Stay Time on ELOR Mission Safe Return

potential LM concepts are related to stay time and P_{90}. The unmodified Apollo LM is limited because of the battery life, and, therefore, is not a serious contender. Using the SNAP-27 provided an EPS P_{90} of nearly 1.0. Beyond that, as indicated in Table 13, the remaining weakness is in the environmental control and, more specifically, the heat transport loop, the only operating function during the dormant mode. In that system, provisions for module replacement will resolve any other potential weaknesses.

The recommended LM will meet the 90-day ELOR requirement with a P_{90} probably greater than 0.99. The probability of an abort due to a LM system failure is expected to be less than for the CSM because of the less complex quiescent mode control; it should not exceed $P_a = 0.003$. That means only three chances in one thousand of having to abort due to a LM system failure. This is because only a part of the communications, the environmental control, and electrical power systems must operate during the quiescent state. The LM contribution to P_s may be somewhat lower than the DRM because of increased system complexity for the third man. However, planned maintenance can offset this.

Assessing Crew Safe Return

Since abort is constrained only by departure windows, the P_s for the manned phases should approach or exceed the value established for Apollo, i.e., 0.999. It approaches that value based on the premise that the systems supporting the manned phases, for the most part, operate about 24 percent less than for the Apollo design reference mission (DRM-2A), and no deleterious effects are expected from the quiescent phase. It may exceed the actual value because of planned maintenance for potential system weaknesses.

*See definitions on page 16.

The situation can best be understood through analysis of the data as presented in Figure 10. Note that the LM has only four functions that contribute to the probability of completing the 90 days without an uncompensated failure, two of which contribute some degradation to P_s. The remaining LM functions are not operated until departure.

The CSM has one more function and some additional complexity in the others; all of which adds up to a slightly higher chance of abort ($P_a = 0.01$). Again two of the five functions contribute some degradation to P_s.

As for the functions affecting P_s, the combination of the three modules without the effects of the quiescent state use must be $P_s \geq 0.999$, the Apollo II objective. Therefore, the total P_s for the ELOR mission is the product of those estimated for the Apollo DRM and the ELOR quiescent phase, or about $P_s = 0.992$ without provisions for additional maintenance. The repair kit for meteoroid damage will raise the P_s to or over $P_s = 0.999$.

The one constraining factor associated with the foregoing is the launch window from the lunar surface. To approach the Apollo DRM safety, it may be necessary to rendezvous with the orbiting CSM within two hours, with the CSM in a high-inclination orbit, this may be impractical for some sites on the surface. With minimum fuel margins, it could be necessary to wait for up to 14 days. Again, provisions for planned maintenance will permit much longer delays, the amount depending on the failure mechanism. The one grey area of any concern is the CSM ELOR stability control.

In summary, there is reasonably good data to support the belief that safe return of the ELOR crew can be accomplished within the same or better risk as that associated with the Apollo DRM.

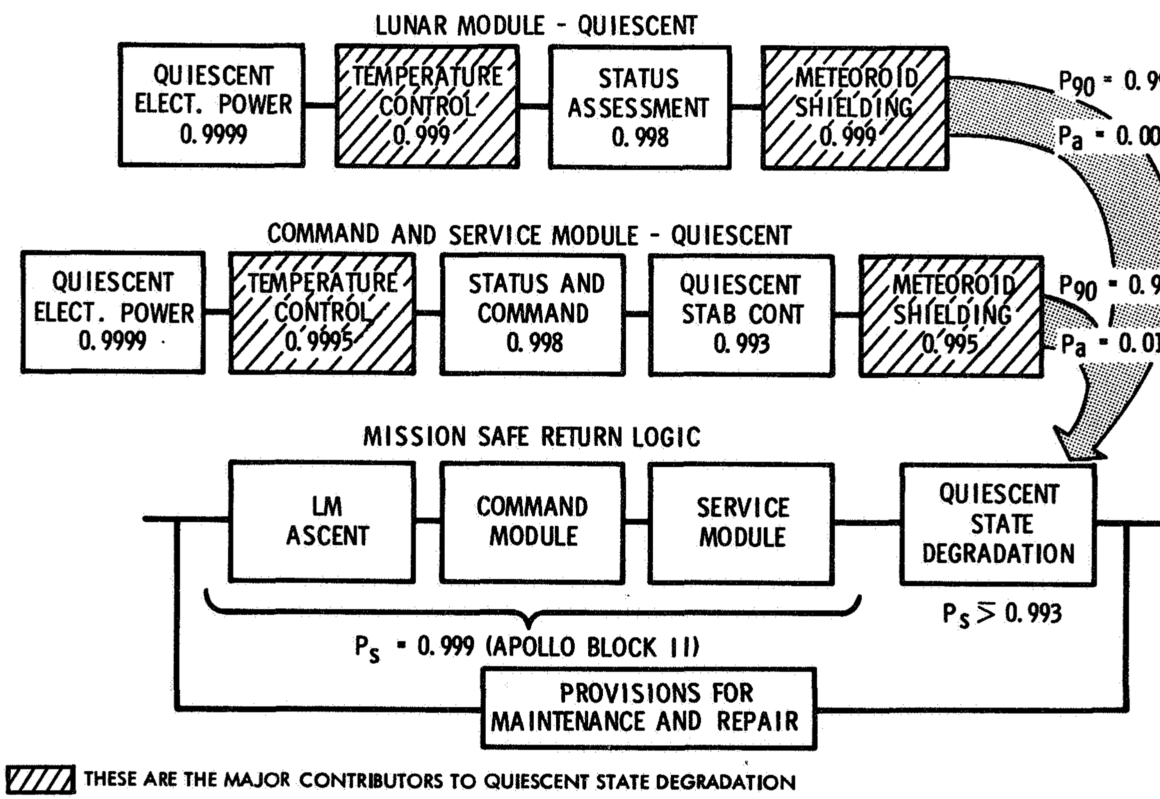


Figure 10. Assessing ELOR Mission Safety

Table 11. CM Recommendations for Crew Safe Return Assurance, Beyond Block II

Subsystem	Estimated Reliability	Improvement Technique	Spares or Redundancy	ELOR P_{90}	Qualification Status
Electrical power	0.994	Add SNAP-27A, a dual system, add redundant inverter	1*	>0.9999	Completed
Environment control	<0.9	Modify ECS coolant loop, add quiescent loop	1	0.9995	95%
Guidance and navigation	0.98	Provide spares or cannibalize LM before departure	4	0.99	Completed
Stability control	0.91	Shutdown SCS, use sun sensor/ESS and switchable redundancy	7*	0.993	80%
Communications and data	0.86	Use switchable redundancy and duty cycle control	2**	0.998	Completed
Reaction control	>0.999	None	0	0.9999	95%
Up-data link	0.97	Add remote switched redundant unit	1**	0.998	Completed
Central timing	0.997	Shut down during dormant mode	0	0.9998	Completed
Earth landing	>0.9999	None	0	0.9999	Completed

*Redundant elements
**May be used either way

Table 12. SM Recommendations for Crew Safe Return Assurance

Subsystem	Estimated Reliability	Improvement Technique	Spare	ELOR P_{90}	Qualification Status
Electrical power plant	0.994	Shut down during dormant phase (use SNAP-27A)	0	0.9999	80%
SM reaction control	0.996	Aluminize positive explusion tanks Block II redundant quads all right	0	0.99999	Completed
SM propulsion	0.996	No change or R&M required	0	0.996	Completed
Propellant storage	0.9999	No R&M required	0	0.99999	Completed*
Propellant control	0.9999	No R&M required	0	0.9999	Completed*
Deep space antenna	0.9991	No R&M required	0	NA	Completed
Cryogenic storage	0.9999	No R&M required	0	0.9999	Completed*
SM structure	0.2	Patching kit desirable	Kit	0.995	80%

*These are qualified for the SD concept but not for the LMSC recommendation

Table 13. LM Ascent Stage Recommendations for Crew Safe Return Assurance

Subsystem	Estimated Reliability	Improvement Technique	Spares	ELOR P_{90}	Qualification Status
Electrical power	0.96	No M&R required (use longer life batteries)	0	>0.99999	90%
Environmental control	0.8	Operate P/O heat transport loop only during quiescent, provide for replacement of the pump motor	1	0.999	90%
Guidance and navigation	0.99	Provide for recommended M&R	5	0.999**	Completed*
Stability control	0.993	Could be improved through spare	-	0.993**	Completed
Reaction control	0.93	No M&R or other required	0	>0.99999	Completed
Communications	0.99	Provide for recommended M&R	2	[.998]	70%
Ascent propulsion	0.995	No M&R required	0	0.995	Completed
Structure	>0.999	[Patching kit may be desirable]	0	>0.999	95%

*Except for determination of heater requirement during a dormant phase
**P_s greater than Apollo mission without spares.
[ ]Does not contribute to P_s.

Table 14. LM Descent Stage Recommendations for Crew Safe Return Assurance

Subsystem	Estimated Reliability	Improvement Technique	Spare	ELOR P_{90}	Qualification Status
Electrical power*	≈1.0	No R&M required	0	≈1.0	70%
Descent propulsion	0.997	No requirement	0	>0.997	Qualified
Descent structure	>0.999	No requirement	0	>0.999	50%

*SD/Grumman recommended concept, using SNAP-27

MAINTENANCE AND REPAIR (M&R) REQUIREMENTS AND RAMIFICATIONS

M&R for the CSM

During the 2200-hour quiescent phase when the CSM is unattended, failures in operating systems can be the most critical. However, since most of the CSM functions are not required to operate during the quiescent phase; failures that occur in the non-operating functions can be repaired after crew return and before transearth injection if these repairs are planned for. Potential failures in the remaining quiescent-critical functions are compensated for by either providing redundant elements or switchable spares. Further, crew safe return can be accomplished through use of a backup function which is activated from the earth MSFN or a lunar surface control function. In those cases, the lunar party may have to abort to the orbiting CSM to make a repair or return to earth.

In the example used, the ELOR stability system (ESS) establishes and maintains the slow roll and dampens out wobble. If it fails after using the switchable spares (7 chances in 1000), the CSM can be returned to the normal mode (Block II SCS), and abort is initiated as soon as possible without a serious detriment to P_s.

The most pronounced weakness was found to be created by the meteoroid hazard; there was a very high probability (0.8) of some form of penetration. It was compensated for through some shielding (a form of redundancy) and planned repair. A patching kit is recommended for repair of the CM heat shield in particular, which will easily compensate for any realistic risk level.

The result of the analysis for the CSM indicated that even though some form of maintenance is not practical for the quiescent phase, the combination of switchable redundancy, abort capability and six to eight spares plus a repair kit amounting to less than 200 pounds to be used after crew return will provide a P_s in excess of 0.99. Most of this weight (143 pounds) could be eliminated through provisions to cannibalize the LM. Theoretically CSM ELOR could be a safer mission than Apollo.

M&R for the LM

The LM is in a quiescent state both in transit to the moon and while on the lunar surface, the combination of which, makes up most of the ELOR mission. The time on the lunar surface (some 2200 hours) presents the greatest failure hazard period. As indicated in Tables 13 and 14, only eight spares were required to raise the P_{90} from 0.7 to over 0.99 for the full 90 days. These spares weigh less than 200 pounds. Further, five of these are required for the G&N system to be used just before launch. These same units could be used as spares for the CSM G&N system, eliminating about 140 pounds between the two vehicles, if the logistic problems could be worked out; if not they are not required to achieve the Apollo goal for the G&N system.

The LM, although not designed for maintenance, can be reached by the lunar party at any time. Therefore, no LM system emergency should create an abort situation. A safer alternative is to make a repair. The only possible exception would be an emergency involving the SNAP 27, which is considered improbable. Maintenance of the LM involves replacement at the box level, which is now possible with little or no design change.

CONCLUSIONS

The study of the application of the data derived from a study of mission duration extension problems to the ELOR mission has shown that contemporary space systems can be used to meet the needs of manned extended missions of up to 90 days duration. The ELOR is brought well within the realm of possibility through natural extensions of contemporary subsystems' capability by application of such recognized systems engineering processes as operational control, fail-safe design, redundant functions, and, most effective of all, planned maintenance and repair (Figure 11).

Perhaps the most profound result of the study was that as few as 15 repair or replacement actions could raise the probability of completing the 90-day mission without abort to over 0.99 from about 0.5. These repair and replacement actions have been specifically identified and are known to be feasible with little or no modifications to Block II configurations (see Tables 11 through 14). Further, the probability of safe return is expected to exceed that for Apollo II.

The ability to specifically identify required maintenance action before the mission and during the development phases is paramount to this mission concept. Modern technology has contributed greatly, and the baseline study is directed toward this end. A summary of the results concerning specific identification and location of potential failures is in "Space Systems Malfunction Isolation, Luck or Logic," a paper presented by Roy Carpenter of SD at the Second National Conference on Space Maintenance and Extravehicular Activity, 7 Aug. 1968 in Las Vegas. It develops the logic associated with the process and demonstrates its applications.

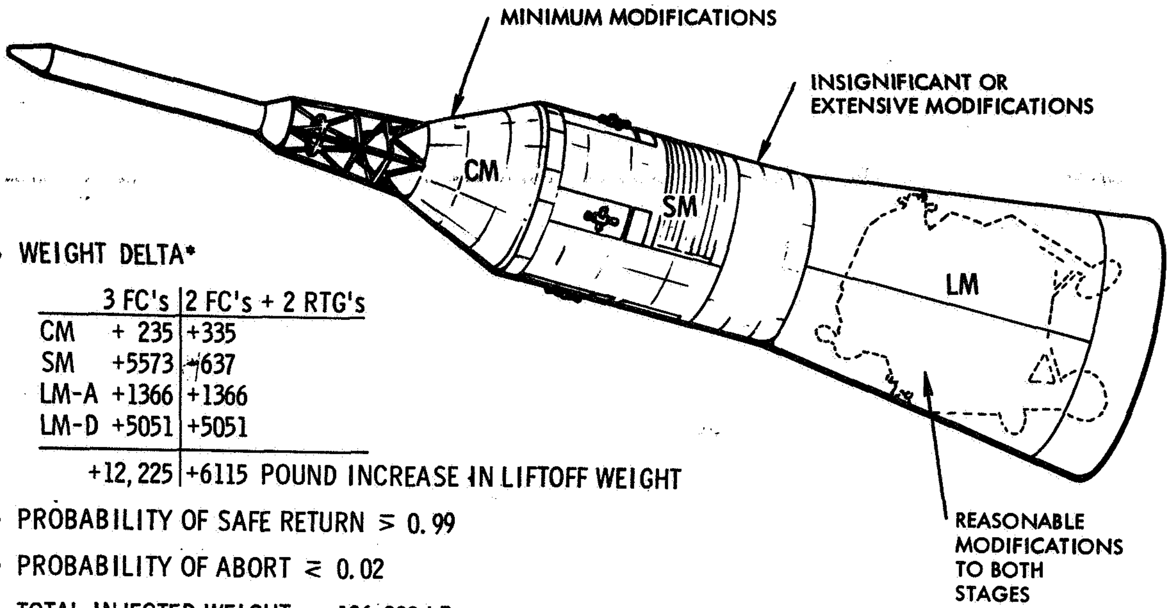
The development requirements associated with the ELOR, as recommended by the SD team, involves a very modest program when compared to contemporary space programs. The development cycle should not exceed 3-1/2 years; the pacing components vary with the selected concept, and the LM stages require the greatest modifications.

The mission is at least as safe as Apollo, it is the most conservative approach to extended lunar exploration, it can be implemented within the 1970-1975 time frame, and it demonstrates the effectiveness of even the crudest form of maintenance planning on extended mission safety. Perhaps most significant of all is that the injected weight into translunar phase need not exceed about 106,000 pounds, about 4,000 pounds over the present Saturn V capability.

SUPPORTING DEVELOPMENT AND RESEARCH

The ELOR mission does not call for a completely new development program and is not a great departure from the Apollo design reference mission (DRM-2A). The overall manned operations have decreased by about 25 percent for the CSM and 33 percent for the LM. The major differences are created by the need to maintain optimum storage conditions. Further, the ramifications of the third man on the LM has created the most extensive changes and, therefore, the pacing factors for the ELOR development program.

The projected development program for the ELOR vehicles are presented in Figure 12. The LM is expected to take about six months more than the CSM because of the more extensive modifications required to both the ascent and descent stages.



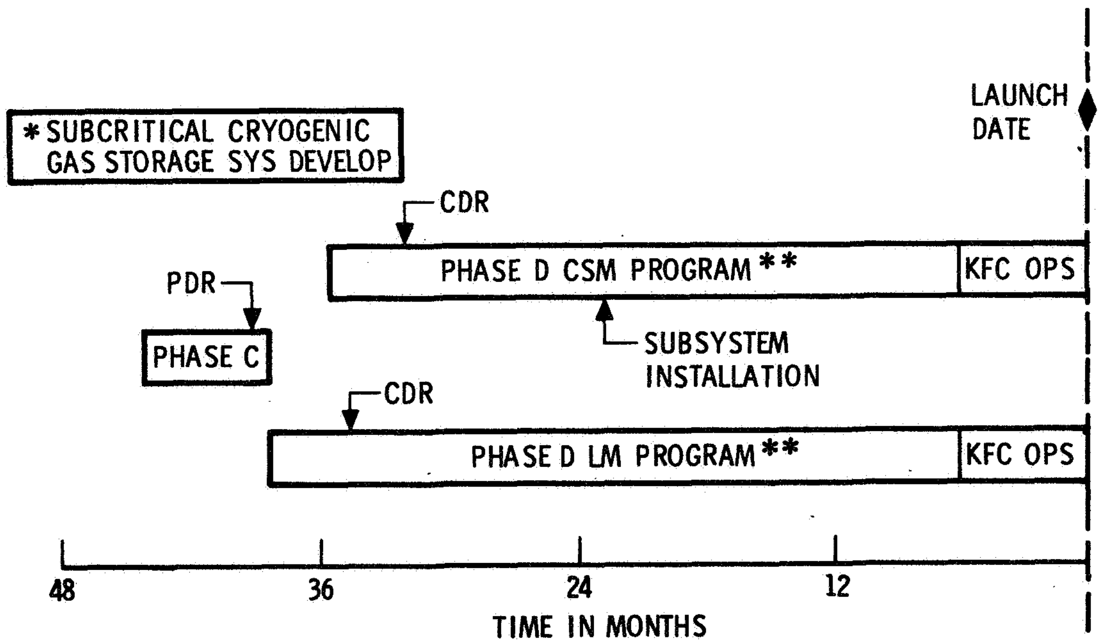
- WEIGHT DELTA*

	3 FC's	2 FC's + 2 RTG's
CM	+ 235	+335
SM	+5573	+637
LM-A	+1366	+1366
LM-D	+5051	+5051
	+12,225	+6115 POUND INCREASE IN LIFTOFF WEIGHT

- PROBABILITY OF SAFE RETURN ≥ 0.99
- PROBABILITY OF ABORT ≤ 0.02
- TOTAL INJECTED WEIGHT ≈ 106,000 LB
- 15 SPECIFIC REPAIR OR REPLACEMENT ACTIONS WITH ACCOMMODATING DESIGN

* USING SC 107 BASELINE

Figure 11. Mission System Summary



*REQUIRED FOR LMSC CONCEPT ONLY
**BASED ON THE ASSUMPTION THAT AN ADDITIONAL GROUND TEST VEHICLE IS AVAILABLE

Figure 12. ELOR Vehicle Development Program

The major problem area in the development cycle is that introduced by the potential requirement for subcritical cryogenic storage systems. If these are considered a requirement (not recommended by SD), a two-year subsystem development program is required to prepare them for vehicle integration. The result is that the ELOR development program would be stretched from a conservative 3-1/2 year cycle to nearly 4-1/2 years. (This includes both Phases C and D.)

Some of the major development items or test programs to be considered include:

1. Qualification of subsystems functions to be operating for the 90 days
2. Manned rendezvous and docking of the LM to an unmanned CSM.
3. LM ascent and descent propellant tanks
4. LM and CSM thermal conditions and control techniques for the dormant phases
5. LM and CSM environmental control system modification
6. New and modified subsystem fit and compatibility verification.
7. New electrical power source for both LM and CSM (needs qualification and compatability demonstration)
8. Status monitor for LM and CSM
9. ELOR stability control for CSM
10. CSM command demodulator/decoder
11. 3-man LM vehicle development
12. Subcritical cryogenic gas storage system*

*(Not required for recommended concept)

The study identified the development of the command link for the manned rendezvous and dock of the LM to an unmanned command module as a long lead item. Early implementation of command link development may allow man-rating to be accomplished, as an additional task, on one of the latter Apollo flights.